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EXTENSIONS TO THE LEARNING CURVE: AN ANALYSIS OF FACTORS INFLUENCING UNIT COST OF WEAPON SYSTEMS

by

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The use of learning curves to analyze unit costs experienced during the manufacture of items produced from a repetitive process is widespread. The assumption implicit in the use of learning curves is that cumulative quantity produced is the primary factor influencing the pattern of unit costs. This paper adds to the learning curve model variables reflecting production rate, company-wide activity and fixed costs, and industry activity. Empirical tests conducted using data from missile weapon systems show that each variable enhances the explanation of unit cost but the importance of the variables depends on the nature of the cost series being analyzed. Additional tests examine the influence of broader economic and political factors on weapon system unit cost.

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EXTENSIONS TO THE LEARNING CURVE:
AN ANALYSIS OF FACTORS INFLUENCING
UNIT COST OF WEAPON SYSTEMS

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PREFACE

This study was conducted for the Naval Sea Systems Command's Cost Estimating and Analysis Division, Code 017. Funding was provided under the Naval Postgraduate School direct funding allotment, Project Code 54M01.

This study represents a continuation of a line of research initiated in FY 1989 and reported in "Estimating and Explaining the Production Cost of High Technology Systems: The Case of Military Aircraft", Naval Postgraduate School Technical Report No. 54-89-07. A portion of that report provided a preliminary analysis of relationships between program cost and a collection of environmental and financial factors. This current study continues to investigate factors that influence program cost.

As outlined in the 12 July 89 "Memorandum of Understanding", the current research was to examine cost drivers during the acquisition of major weapon systems. Year-by-year cost patterns were to be investigated, with a focus on ship-based weapon systems. The guiding research question was to be "what factors appear to cause escalation (or decline) in the cost of weapon systems as an acquisition program proceeds over time?"

Although a continuation of a prior line of research, this report is a self-contained document. The report is submitted in fulfillment of the agreement outlined in the Memorandum of Understanding. The report is releasable.

EXTENSIONS TO THE LEARNING CURVE: AN ANALYSIS OF FACTORS INFLUENCING UNIT COST OF WEAPON SYSTEMS

Learning curves have gained widespread acceptance as a tool for analyzing, explaining and predicting the behavior of unit costs of items produced from a repetitive production process. (See Yelle, 1979, for a review of learning curve literature.) Cost estimation techniques for planning the cost of acquiring weapon systems by the Department of Defense, for example, typically consider the role of learning in the estimation process. The premise of learning curve theory is that the cumulative quantity of units produced is the primary "driver" of the cost of those units. Unit cost is expected to decline as cumulative quantity increases.

Past research has attempted to augment learning curve models by including additional variables. Most attention has been focused on the addition of a production rate term. This study continues that line of analysis. The broad objective is to identify factors (i.e., cost drivers) that may be expected to impact the unit cost of items produced from a repetitive production process, develop empirical surrogates for those factors, "enhance" traditional learning curve models by including the factors in models, and examine the conditions under which such factors appear to be important explainers of cost.

The paper starts by presenting some simplified functional models of the factors that should drive unit cost, the purpose being to identify plausible candidate variables for inclusion in

learning curve models. Empirical models incorporating these candidate variables are then presented, along with comments on past related research. Hypotheses reflecting the expected associations between cost drivers and unit cost, under differing circumstances, are offered. Tests of the hypotheses using data from a sample of eight ship-based tactical missile systems are conducted. Later analysis then examines prediction errors from the models and additionally explores some possible explanations of the prediction errors.

MODELS AND HYPOTHESES

FUNCTIONAL MODELS

The purpose of this section is to present some simple functional models of unit cost. All models are simplified representations of phenomena, all make assumptions, and none are fully valid. The objective here is to use the models as a basis for talking through some issues.

At the most basic level the cost of any unit is just the sum of the variable cost directly incurred in creating the unit and the share of fixed costs assigned to the unit, where the amount fixed costs assigned depend on the number of units produced.

$$UC = VC + \frac{FC}{PQ} \qquad (1)$$

where

UC = Unit cost
VC = Variable cost per unit
FC = Total fixed costs per period
PQ = Production quantity per period

Now let's refine the model to incorporate the effect of

"learning." The fact that labor costs and material costs per unit tend to decline with successive units produced in a repetitive production process is well recognized. Employees "learn" the production tasks, reducing both labor time and material usage. An assumption here is that learning impacts variable costs. Hence

$$VC_Q = VC_1 \quad Q^b \qquad (2)$$

where

Q = Cumulative Quantity

VC_Q = Variable cost of the Qth unit.

VC_1 = Variable cost of the first unit.

b = Parameter, the learning index, assumed to be negative.

Substituting into equation (1):

$$UC_Q = VC_1 \quad Q^b \quad + \frac{FC}{PQ} \qquad (3)$$

This model incorporates the two factors presumed to impact unit costs that have been most extensively investigated: learning (Q^b) and production quantities (PQ). Smith (1980, 1981), for example, used a model analogous to equation (3) to explore the effect of different production rates on unit cost. Balut (1981) and Balut, Gulledge and Womer (1989) construct models based on learning and production quantity to assist in "redistributing" overhead and "repricing" unit costs when changes in production rate occur.[1]

Equation (3) is limited because it implicitly assumes that

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[1]The Balut and Balut, Gulledge and Womer models differ in that they determine a learning rate for total (not variable) unit cost and then apply an adjustment factor to allow for the impact of varying production quantity on the amount of fixed cost included in total cost.

only one kind of item is produced and hence all costs (variable and fixed) are "direct" or associated with that item. In reality, of course, firms typically produce multiple items and incur plant-wide or company-wide costs that are indirect and then allocated to a specific item. Equation (3) can be refined to incorporate this idea as follows:[2]

$$UC_Q = VC_1 \; Q^b + \frac{DFC}{PQ} + \frac{IFC}{PQ+OQ} \qquad (4)$$

where

DFC = Direct fixed cost per period

IFC = Indirect fixed cost per period

OQ = Other quantities -- production quantity per period of items other than that being costed, measured in units equivalent to PQ.

In this model the contribution of indirect cost (IFC) to unit cost (UC) depends both on the production quantity of the item being costed (PQ) and on the production quantity of other items being produced (OQ). For simplicity, production quantity and other quantity can be combined into CQ, the company-wide quantity (i.e., CQ = PQ + OQ) and substituted into equation (4):

$$UC_Q = VC_1 \; Q^b + \frac{DFC}{PQ} + \frac{IFC}{CQ} \qquad (5)$$

Of course, this model is still a simplification. Most firms have several organizational levels and whether costs are direct or indirect depend on the level referenced. Multiple items can be made in one plant, multiple plants may exist in one division,

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[2]The formulation assumes that only fixed costs are indirect, i.e., that all variable costs, because they vary with units of output, can be directly associated with units of output.

multiple divisions in one firm. Costs that are direct at one level may be indirect at a lower level, and the process of allocating indirect costs to lower levels may be complex. The model does, however, convey the idea that assignment to costs to units depend on various different measures of volume or quantity.

Last, assume the existence of a "standard" ("benchmark," "normal," "planned") production quantity (PQ_s). Standard direct fixed costs per unit (SDFC) at the standard production quantity would be:

$$SDFC = \frac{DFC}{PQ_s} \qquad (6)$$

The production rate (PR) for any period can then be expressed as a ratio of the production quantity to the standard quantity:

$$PR = \frac{PQ}{PQ_s} \qquad (7)$$

The second term of equation (5) can then be rewritten as:

$$\frac{DFC}{PQ} = \frac{SDFC}{PR} \qquad (8)$$

Assuming a standard company-wide quantity and using analogous reasoning, the third term of equation (5) can be rewritten as a ratio of standard indirect fixed cost per unit (SIFC) and a company rate (CR):

$$\frac{IFC}{AQ} = \frac{SIFC}{CR} \qquad (9)$$

and equation (5) rewritten as:

$$UC_Q = VC_1 \ Q^b + SDFC\ (PR^{-1}) + SIFC\ (CR^{-1}) \qquad (10)$$

In this final formulation it can be seen that total cost per unit is the sum of variable cost per unit (adjusted for learning)

plus standard direct fixed cost per unit (adjusted for production rate), plus standard indirect fixed cost per unit (adjusted for company rate).

Under the heroic (and no doubt invalid) assumption that changes in any variable on the right hand side of equation (10) do not necessitate changes in any other variable (i.e., ceteris paribus), predictions of the impact on unit cost of changes in any of the variables is straight forward:

a) Unit cost will decrease with increases in cumulative quantity, but at a slower rate as cumulative quantity increases. (The relationship is a power function with exponent b. The first derivative of UC with respect to Q is negative, the second derivative is positive.)

b) Unit cost will decrease with increases in production rate per period, but at a slower rate at higher production rates. (The relationship is a power function with exponent -1. The first derivative of UC with respect to PR is negative, the second positive.)

c) Unit cost will decrease with increases in the company rate per period, but at a slower rate at higher company rates. (The relationship is a power function with the exponent -1. The first derivative of UC with respect to CR is negative, the second positive.)

d) Unit cost will increase with increases in variable or fixed costs, at a constant rate. (The relationship of UC with VC_1 and SDFC and SIFC is linear.)

Of course, in reality, the ceteris paribus assumption is unlikely to hold. This is because there are numerous potential interrelationships and interactions between the variables on the right hand side of equation (10) that can come into play in a dynamic environment. Some examples:

a) Variable costs and fixed costs are interdependent. The issue here is one of cost structure (or operating leverage). Firms can tradeoff the incurrence of variable costs versus fixed costs to achieve an output. An obvious example is automation, which tends to increase fixed (plant) costs but reduce variable (labor) costs. The impact on total unit cost is ambiguous. McCullough and Balut (1986) provide evidence that the fixed component of cost is increasing as industry moves toward automation.

b) Variable cost and production rate are interdependent. While increased production rate should reduce fixed cost per unit, the impact on total cost per unit is ambiguous because production rate may also influence variable cost. The conventional view (e.g., Bemis, 1981; Cox and Gansler, 1981) is that there are both economies and diseconomies of scale, resulting in a U-shaped relationship between total unit cost and production rate. As rate increases, unit cost initially declines, due to such factors as reduction of fixed cost per unit, reduction of variable material cost per unit (more economical quantity purchases) and reduction in variable labor cost per unit (less labor time waste). After an optimum is reached, increases in production rate result in higher total unit cost because increases in variable costs more than

offset the additional reduction in fixed cost per unit. One cause might be the increase in variable labor costs due to the necessity of overtime. Past research (Smith, 1976) has found that production rate can be an important explainer of labor costs. Similar interactions between variable costs and the company rate would also apply.

c) Production rate and company rate are interrelated. It is obvious that PR and CR are not independent because production quantity is one element that makes up the company-wide quantity. Ceteris paribus, when PR increases, CR increases (but at a slower rate). They also interact in a less obvious way due to capacity constraints. Given a finite productive capacity, increases in PQ potentially constrain OQ and vice versa.

d) Direct and indirect fixed costs may be interrelated. In principle direct and indirect fixed costs are distinct. In practice what fixed costs are considered direct and what are considered indirect is a function of a firm's accounting system. The definition of a firm's accounting cost pools and the procedures for assigning costs to pools, and then to units produced, can influence the final determination of whether a cost is direct or indirect.

e) Fixed costs and production quantity are interrelated. It is typical for a firm to plan the level of some fixed costs (e.g., plant, equipment, staff) on the basis of some anticipated production quantity, starting at a low level for initial units produced and building capacity as production quantities increase.

Thus, for example, increased production rate could be associated with increases in total unit cost if fixed costs were increased more than proportionately with the increased production.

f) Cumulative quantity and production rate are interrelated. This is true in the obvious functional sense that cumulative quantity over several periods is the sum of all production quantities in each period. Additionally there tends to be an empirical relationship due to the tendency for the initial production rate for a new product to be low relative to rates typical in later periods, when the design is mature and the "bugs" worked out of the process (Boger and Liao, 1990). This causes a positive correlation between cumulative quantity and production quantity per period (low values of both in early periods, high values in later periods). Gulledge and Womer (1986), among others, document this association.

Additional complexity can be added by altering the perspective from which "cost" is viewed. More specifically, equation (10) treats cost from the perspective of the manufacturer. Many applications are concerned with cost to the buyer, which is price to the manufacturer, and typically includes a fee, particularly if procurement occurs under some cost plus arrangement. Thus the equation for unit cost becomes:

$$UC_Q = VC_1 \; Q^b + SDFC\,(PR^{-1}) + SIFC\,(CR^{-1}) + Fee \qquad (11)$$

Obviously unit cost now additionally depends on the mechanism underlying the calculation of the fee. Without exploring the details, suffice it to say, that fee may be constant, may be tied

to total costs, may be functionally related to components of cost (such as facilities employed) or may involve a combination of arrangements. For those interested White and Hendrix (1984) provide a review of contract types and fee arrangements.

The broad conclusion to be drawn from the discussion above is that the factors affecting unit cost are sufficiently numerous, and the interactions between factors sufficiently complex, that attempts to develop functional models to be used to either estimate or explain costs are difficult. Complete models would require extensive data and be virtually a reproduction of a firm's cost accounting system. Hence, most initial attempts to develop cost estimating relationships (CERs) tend to be empirically (statistically) based and rest on the assumption that complex functional relationships can be represented by simple statistical relationships, relationships that exist due to regularities in the data. But a functional model can serve as a basis for selecting variables to be included in a statistical model and for hypothesizing the form of the relationship between variables. The next section presents statistically based cost models, informed by knowledge of functional relationships.

EMPIRICAL MODELS

Learning Curves: The most common statistical cost model is the familiar learning curve model:

$$UC_Q = a\ Q^b \qquad (12)$$

where

UC_Q = Average unit cost at quantity Q.

a = Theoretical first unit cost, a parameter to be estimated.

Q = Algebraic midpoint of a particular production lot.

b = Learning curve exponent, a parameter to be estimated.

The model has gained wide acceptance in practice.[3] Note that the learning "adjustment" (Q^b) is applied to total unit cost (a) not just to variable unit cost as in the functional models. The implicit assumption is that total cost is related to quantity in the same manner that variable cost is, which is clearly not the case. So this learning curve model is perhaps best thought of as a cost improvement model -- where cost improvement is due to a number of factors, including traditional "learning". Gold (1981) comments on this:

> ". . . most internal improvements. . . represent the results not of cumulative repetition of past practices, but of changes in: product designs; product mix; operating technology; facilities and equipment; management, planning and control; materials quality; and labor capabilities and incentives. And such changes result from the active exploration and development of superior alternatives to past practices by research personnel, design engineers, production specialists, and supervisory staff. This may also be termed 'learning'--if that term means nothing more than the summation of all improvements regardless of cause.

In short the parameter b is presumed to capture a collection of

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[3]Note that this is an incremented unit cost model rather than a cumulative average cost model. Liao (1988) discusses the differences between the two approaches to learning curve models and discusses why the incremental model has become dominant in practice. One reason is that the cumulative model weights early observations more heavily and, in effect, "smooths" away period-to-period changes in average cost. Since one purpose of this study is to explore reasons for period-to-period cost changes, the incremental model is more appropriate.

effects which in the functional model (equation 10) are separately reflected in the various rate and fixed costs terms.

Rate models: Recent attempts to improve cost models have focused on adding an additional term, reflecting some measure of rate or activity, to the learning curve model. Approaches differed depending on the level of aggregation at which activity was viewed. Consider three levels of aggregation and indicators of rate or activity associated with each:

Product: Product production rate (PR)
Company: Company-wide activity rate (CR)
Industry: Industry capacity utilization rate (IR)

Note that two terms (PR and CR) are components of equation (10) while IR is a more aggregated, non-firm specific indicator of activity.

Most attempts to augment the learning curve model have added a production rate term (e.g., Alchian, 1963; Bemis, 1981; Cox and Gansler, 1981; Greer and Liao, 1986; Hirsch, 1952; Large, Hoffmayer and Kontrovich, 1974; Womer, 1979) as follows:

$$UC_Q = a\ Q^b\ PR^d \qquad (13)$$

Smith (1980) reviewed many of the production rate studies. The general conclusion to be drawn from the studies as a group is that attempts to improve cost models by inclusion of production rate have not been very successful. In some cases the production rate term is a significant explainer of cost, in many it is not. In some cases production rate is negatively associated with cost, in others it is positive. The specific effect of production rate appears to vary across systems studied.

Several explanations can be offered. 1) A focus on production rate for a single product is too limited, ignoring the impact of broader activity changes in a firm. 2) A focus on production rate alone fails to incorporate and control for other concurrent changes, such as the changing level of fixed costs that are to be distributed over the production quantities. 3) Varying results are to be expected because rate changes can lead to both economies and diseconomies of scale. 4) Production rate effects are difficult to isolate empirically because of the colinearity with cumulative quantity. 5) Researchers have usually used total production "quantity" as a measure of production "rate", which leads to misspecified models (see Boger and Liao, 1990, for elaboration).

More recent work by Greer and Liao (1983, 1984, 1986, 1987) augments the learning curve model by adding a measure of industry activity, industry capacity utilization (IR):

$$UC_Q = aQ^b \; PR^d \; IR^g \tag{14}$$

Much of their analysis was concerned with the effect of industry capacity utilization on competition and pricing for duel-sourced weapon systems. But some results were provided for sole-sourced systems and it is this later analysis (1984, 1986) that is most relevant here:

> There is some cause effect similarity between price changes induced by changes in capacity utilization and changes in production rate, R--under sole sourcing. In either case, fixed costs attach to different quantities of output. However, capacity utilization changes reflect changes in overall corporate output. A rate change (R) by itself causes only a change in the allocation of those fixed costs that originate in the facility (or segment) used for the program

> in question. Either of these changes can occur independently of the other, depending on what is taking place in the rest of the firm. The two will be identical only if the program of interest is the firm's only source of revenue. (Greer and Liao, 1987, p. 279)

> Indirect costs are incurred at both the plant level and the corporate level. Changes in a plant's production rate affects the allocation of plant level indirect costs to final cost objectives (contracts), but, are of relatively minor importance to the allocation of corporate indirect costs. The allocation of corporate indirect costs is more closely related to the overall business volume of the firm. (Greer and Liao, 1987, p. 275)

Their findings indicated that capacity utilization has a more important effect on unit cost than does production rate, most likely because individual programs represent only a small element of a firm's full business activity.

The significance of IR as a cost driver suggests that it captures something relevant to "activity" and hence to cost estimation. The obvious issue is the degree to which an industry capacity utilization measure serves as a useful proxy for firm-specific activity,[4] and whether an explicit firm-specific measure can improve cost models. This, of course, suggests an additional augmentation to the learning curve model by the inclusion of a company-specific activity rate (CR) term.

$$UC_Q = aQ^b\ PR^d\ CR^f\ IR^g \qquad (15)$$

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[4]Greer and Liao (1984) appropriately justify the use of industry capacity utilization rather than a firm-specific activity measure--in their analysis of duel source competition--by arguing that the objective was to capture "general business conditions" not firm-specific activity. This justification is perhaps less applicable in their analysis of sole-source programs where industry capacity utilization is explicitly argued to be a proxy for firm-specific activity.

Evidence on the role of a company-specific activity rate measure is not available.

Note that PR, CR, and IR are all measures of activity, at different levels of aggregation. PR and CR are direct components of the functional model discussed previously (equation 10). If the functional model is "correct," and PR and CR capture the activity factors that should influence cost, is IR then redundant? Two points argue for the additional relevance of IR. First, empirically any measures of PR or CR are likely to be measured with error. Hence, IR may reflect some aspect of firm specific activity "missed" by PR and CR measures. Second, industry capacity utilization could impact cost indirectly through an impact on some specific cost elements. Any manufacturer must acquire some factors of production externally. High levels of capacity utilization could be consistent with high supplier activity and consequently low supplier per unit costs. This could result in low acquisition cost of production factors (e.g., materials) and consequently low manufacturing cost. If such an indirect effect were to occur, it would not be captured by either PR or CR. In short, at least in principle, IR is potentially a non-redundant explainer of cost.

<u>Fixed Capacity Costs</u>: The reason for including PR and CR in a cost model is to incorporate the effects of spreading fixed capacity costs over varying output. (These variables are denominators of the second and third terms in equation 10). But the impact of PR and CR on unit cost is influenced by any change in the amount of fixed costs to be spread. This notion, of course,

is not new (see, for example, Boger and Liao, 1990) but its incorporation in cost models is generally lacking. The impact of a change in fixed costs on unit cost is constant at all levels of fixed cost (i.e., the second derivative is zero). In a learning curve model this implies a shift of the curve up or down with changes in fixed cost. To reflect the possible impact of changing fixed costs, the empirical model can be further extended as follows:

$$UC_Q = aQ^b \ PR^d \ CR^f \ IR^g \ e^{hFC} \qquad (16)$$

where

FC = Fixed cost

e = Constant

h = Parameter for FC

UC_Q, Q, PR, CR, IR = Variables previously defined

a, b, d, f, g = parameters

Raising e to the resulting power causes a parallel shift in (the natural log form of) the cost curve.

HYPOTHESES

To the extent that the empirical model (16) reflects relationships implied by the functional model (10), UC_Q should depend on Q, PR, CR, IR, and FC. These independent variables can be considered cost drivers of UC. Ceteris paribus, the expected associations should be those implied by the functional model. Expected associations can be summarized in terms of the expected signs of the parameters in equation (16).

H_1: Unit cost should decrease with increases in cumulative quantity ($b < 0$).

H_2: Unit cost should decrease with increases in production rate ($d < 0$).

H_3: Unit cost should decrease with increases in a company-wide activity rate ($f < 0$).

H_4: Unit cost should decrease with increases in industry activity rate ($g < 0$).

H_5: Unit cost should increase with increases in fixed costs ($h > 0$).

An additional question of interest is whether the variables in model (16) should be expected to be cost drivers under all circumstances. Put another way, should all types of costs be influenced in the same manner by the model (16) cost drivers, or should associations between cost and the factors "depend"? And if they depend, on what? Two issues seem relevant.

New Programs versus Follow-On Programs: Some production programs involve the manufacture of a new design of an item or system; other programs involve the manufacture of a modified or revised design of an existing item or system. For example, some weapon systems are commonly characterized in terms of type, design and series. The B-52a is an aircraft of B type (bomber), design 52, series a. Modifications of existing designs represent a new series (e.g., B-52b). Should the same pattern of "learning" be expected for follow-on series of an existing design as for the first series of a new design? It seems reasonable to argue that considerable learning may occur during the production of a new design; new production techniques are developed and production efficiencies are discovered. Follow-on series should benefit from the learning achieved during the production of the initial series

and the opportunity for additional learning should be less. Some evidence (Moses, 1989) from observing cross sectional differences in learning rates on weapon system programs supports this idea. Stated as an hypothesis:

> H_6: Greater learning should occur on new programs when compared to follow-on programs ($b_{new} < b_{follow\text{-}on}$)

Internal Costs versus External Costs: In a broad sense costs can be segregated into those that are incurred internally by a manufacturing firm and those that result from the acquisition of components externally. If manufacturer A chooses to produce a "part" internally then the cost of that part will reflect material, labor and, most importantly, overhead costs of manufacturer A. The cost of the part will reflect both variable and fixed costs of manufacturer A. If the same part is acquired externally from supplier B, the cost of the part will represent a variable cost to manufacturer A. (Fixed overhead costs may be reflected in the price A pays B for the part, but the cost of the part will then be influenced by the fixed overhead of supplier B rather than manufacturer A.)

An analogy can be drawn in the manufacturer of major weapon systems. Components are often subcontracted out by the prime contractor. Thus total system cost consists in part of "internal" costs, incurred during the production of system components manufactured by the prime contractor and "external" costs representing the cost of acquired subcontracted components. This suggests the broad conclusion that factors relevant to explaining

the cost of components manufactured by a prime contractor may differ from factors relevant to explaining the cost of components manufactured by a subcontractor. Stated another way, the degree to which a model is effective in explaining total system cost may depend on the mixture of prime and subcontractor components that comprise the total system.

Consider the firm-wide activity rate (CR) of a prime contractor. Increasing prime contractor activity should result in the spreading of fixed costs over a larger output and thus reduce the per unit cost of internally produced components. But the activity rate of the prime contractor should have no impact on the spreading of subcontractor fixed costs in manufacturing the subcontracted component. Hence

> $H_{7.1}$: Subcontracted unit costs should not be associated with prime contractor activity rate ($f_{sub} = 0$).

Consider the fixed costs (FC) of the prime contractor. Again increasing fixed costs should result in increasing unit cost, as previously discussed, for components manufactured by the prime contractor. But changes in prime contractor fixed costs say nothing about the cost structure of the subcontractor and consequently should be irrelevant in determining the cost of subcontracted components acquired by the prime contractor.

> $H_{8.1}$: Subcontracted unit costs should not be associated with prime contractor fixed costs ($h_{sub} = 0$).

If subcontracted components are acquired by the prime contractor by some form of cost-based contract then subcontractor activity rate and fixed costs should influence the per unit cost

of subcontracted components. Hence, the per unit price paid by the prime contractor for the components and the per unit cost of the complete system assembled by the prime contractor should be affected. As discussed previously, industry capacity utilization (IR) may represent a surrogate for the degree of business activity of subcontractors and the degree to which subcontractor capacity costs are "spread" to reduce unit cost of components. To the extent that industry capacity utilization does capture "activity" and cost "spreading" of a subcontractor then subcontracted per unit cost should be influenced.

> $H_{9.1}$: Unit cost of subcontracted components should decrease with increases in industry activity ($g_{sub} < 0$).

It was also suggested previously that from the perspective of prime contractor cost, company-activity rate (CR) and fixed costs (FC) may reflect the dominant factors influencing prime contractor cost and that industry activity (IR) could be redundant. Put another way, prime contractor CR and FC are more likely to "matter", and IR is less likely to matter, when explaining prime contractor cost. In constrast, prime contractor CR and FC are less likely to matter, and IR more likely to matter when explaining subcontractor cost. This suggests the general idea that the importance of CR (of the prime contractor) and FC (of the prime contractor) and industry IR in explaining prime versus subcontracted costs should differ.

> $H_{7.2}$: Unit cost of components manufactured by a prime contractor will change (decrease) more strongly with a change (increase) in prime contractor activity rate than will unit cost of components manufactured

by a subcontractor ($f_{prime} < f_{sub}$).

$H_{8.2}$: Unit cost of components manufactured by a prime contractor will change (increase) more strongly with a change (increase) in prime contractor fixed cost than will unit cost of components manufactured by a subcontractor ($h_{prime} > h_{sub}$).

$H_{9.2}$: Unit cost of components manufactured by a subcontractor will change (decrease) more strongly with a change (increase) in industry activity than will unit cost of components manufactured by a prime contractor ($g_{sub} < g_{prime}$).

The effect of prime contractor production rate (PR) on unit cost of subcontracted components is more ambiguous. A change in prime contractor production rate may lead to a change in the rate at which components are ordered from a subcontractor and a subsequent change in subcontractor production rate. Assume the following:

$$PR_{Prime} = \text{Order Rate} = PR_{sub}$$

Increasing PR_{Prime} would increase the order rate, creating higher demand and permitting a higher price charged by the subcontractor. This would (from the perspective of the prime contractor) increase unit cost. But increasing order rate permits increased PR_{sub}, reducing per unit cost to the subcontractor, permitting a lower price to be charged. This would reduce unit cost (from the perspective of the prime contractor).

Alternatively, assuming that $PR_{Prime} \neq \text{Order Rate} \neq PR_{sub}$ is also possible. Changes in PR_{prime} may be anticipated and orders placed early. Or changes in the order rate may be anticipated and PR_{sub} altered early. Thus potential effects of PR_{prime} on unit cost may be modified by anticipation or lags in order rate and PR_{sub}. In

short no unambiguous hypothesis results. At most it might be expected that

> H_{10}: The influence of prime contractor production rate on prime contractor and subcontractor costs may differ ($d_{prime} \neq d_{sub}$).

These hypotheses and other relevant issues will be investigated for a sample of weapon system programs by fitting various versions of model (16) to different cost series and observing the significance of, and relationships between, the various parameters.

METHODS

SAMPLE AND DATA

The sample consisted of eight missile system programs. Cost and quantity data were taken from the U.S. Missile Cost Handbook (Crawford, et. al., 1984), a comprehensive data source for U.S. military missiles. Two initial constraints were placed on the sample: 1. Navy ship-based tactical missiles programs and 2. data availability. The handbook provided some information for 14 ship-based missile programs but cost data was unavailable for four of these, reducing sample size to 10.

Nine of the 10 systems were tactical surface-to-air missiles. The tenth, a strategic/tactical surface-to-surface missile (Tomahawk) was deleted to maintain a consistent mission within the sample.

Observation of the remaining nine revealed that eight had a common manufacturer--General Dynamics--while one system was manufactured by Bendix. The one Bendix system was deleted. It was

felt that the small loss in sample size would be more than offset by the control over firm differences (i.e., organizational structure, accounting systems) gained from having all sample systems produced by the same contractor.

Table 1 contains information on the eight sample systems. The "period" column reflects the period of production for the systems for which data was available. The cost handbook contained cost data aggregated for yearly production lots. The "lots" column indicates the total number of production lots for each program during the period of production. The "follow-on" designation indicates whether a particular system was the first series of a new missile design, or a follow-on series of a previously produced design. Raw data to construct variables came from four sources:

1. Program data on cost and quantity: U.S. Missile Cost Handbook.

2. Firm-specific accounting data: General Dynamics annual reports, 10K reports and Moody's Industrial Manuals.[5]

3. Industry capacity utilization data: Federal Reserve Board reports (reproduced in Greer and Liao, 1983).

4. General Economic and Defense Budget Data: <u>Historical Tables</u> (1990).

All data measured in dollars was inflation-adjusted to 1981 constant dollars. Cost data was available for four distinct cost series:

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[5]General Dynamics produces accounting reports on a calendar year basis, while missile systems are acquired in fiscal year lots. Individual accounting data items were converted to a fiscal year basis by taking a weighted average of data items for the two calendar years that encompassed each fiscal year.

1. Airframe: Airframe, nose piece, rollerons, wing/fin sets, ballast load center, guidance and control, system engineering, project management.

2. Engine: Booster, booster fins, sustainer, engine, rocket motor, gas generator.

3. Other: Miscellaneous

4. Flyaway: Sum of the above.

Table 2 provides a breakdown of the separate cost categories as a percentage of flyaway cost. The analysis was conducted on three cost series, the airframe, engine and total flyaway costs. Flyaway cost was analyzed because it represents the sum of all component costs and is an aggregate measure most often of interest to cost analysts. Airframe cost was analyzed because it is the largest single cost component and is the cost item most directly reflecting the manufacturing activity of the prime contractor. Engine cost was analyzed because it is the largest single cost component subcontracted out. Different subcontractors were used to manufacture the propulsion system for different missile programs. One point of the analysis was to examine different cost behavior (if any) between prime and subcontracted costs.

From Table 2 one may observe that the range of the percentage of airframe cost to flyaway cost is not large (57-67%), consistent with what one might expect of across a set of systems of the same type.

METHODOLOGICAL ISSUES

Several methodological approaches used in the analysis are different from the standard or traditional approaches used in past

TABLE 1

SAMPLE MISSILE PROGRAMS

Program Name	Program Designation	Period	Lots	Follow-On
Tartar	RIM-24B	1961-66	6	No
Terrier	RIM-2D	1961-64	4	No
Terrier	RIM-2E	1961-66	5	No
Standard MR	RIM-66A	1966-70	5	No
Standard ER	RIM-67A	1966-74	8	No
Standard MR	RIM-66B	1971-80	10	Yes
Standard ER	RIM-67B	1973-82	7	Yes
Standard MR	RIM-66E	1981-82	2	Yes
			47	

TABLE 2

COST COMPONENTS

Program	Airframe Cost	Engine Cost	Other Cost	Flyaway Cost
RIM-24B	68%	12%	20%	100%
RIM-2D	61%	18%	21%	100%
RIM-2E	66%	18%	16%	100%
RIM-66A	65%	12%	23%	100%
RIM-67A	58%	24%	18%	100%
RIM-66B	58%	10%	32%	100%
RIM-67B	62%	9%	29%	100%
RIM-66E	68%	10%	22%	100%
Average	63%	14%	23%	100%

research. Some preliminary discussion is necessary concerning three issues.

<u>Pooling of observations</u>. The standard approach to analyzing program cost with learning curve models is to fit a separate model to the observations for each separate program (a time series model). The implicit assumption is that relationships between predictor variables and cost differ from program to program. There are two problems with this approach. First the number of sequential data observations for many programs is typically quite small. Hence many programs are deleted from consideration and the degrees of freedom for programs that do have sufficient data is typically very low. (This may lead to very high but misleading R^2 values for statistically fitted models.) Second, findings are necessarily program specific. General conclusions result only if model parameters are consistent and significant across a set of individual program models, which often is not the case.

The approach used in this study was to pool the observations across the set of programs (typically referred to as a pooled cross-sectional time series analysis.) One benefit is that the number of observations used to fit models and test relationships is increased and hence the power of the tests is increased.

This approach implicitly adopts an alternative assumption that relationships between cost and predictor variables are common across the set of programs pooled. This assumption is more likely to hold if the systems pooled are of a like kind and come from a like production process. (This was one reason for limiting the

sample to ship-launched tactical missile systems and discarding the one system not manufactured by General Dynamics.) The assumption is also consistent with some of the uses of cost models. One purpose of investigating relationships between cost and explanatory variables is to use the relationships to predict future costs. In practice, "learning" experienced on systems already in existence is used as a basis for assessing the learning that can be expected on future systems of the "same type". Given this perspective, an analysis that investigates model parameters for a pooled set of systems of the same type may serve to average away system specific "noise".

Normalization of measures: A problem in pooling observations from multiple programs is that measures of cost (and some factors expected to explain cost) for different individual systems are not comparable. If unit cost for a single system falls from $100 to $80 then something meaningful has happened. If unit cost of one particular system is $100 and that of another system is $80, little of interest can be said--of course the costs are different, the systems are different.

To alleviate this problem, measures that are non-comparable need to be normalized. In general this was achieved by selecting a program-specific average and deflating by (dividing by) the average. Details will be explained later. Normalization of measures would have no impact at all on parameters for individuals explanatory variables if models were constructed only for separate systems. (All observations of a given measure would be deflated

by the same program-specific average. Hence the normalized measure would be linear transformations of the original measures.) When observations are pooled, the choice of deflator has a potential impact on parameter values. Some tests of sensitivity of results to alternative deflators were conducted.

First Difference Models. Traditional approaches to cost modeling attempt to explain the "level" of cost in terms of the level of some explanatory factor, say production rate. An alternative approach is to explain the "change" in cost from one period to another in terms of the change in production rate--an approach based on first differences. If a dependent and independent variable are linearly (log-linearly) related, it can be shown that, in principle, parameter values for the independent variables should be the same in both kinds of models.

The advantage of a first difference model is that variable measures reflect rates of change from period to period. Rates of change measures are comparable across different programs. Hence the choice of the normalizing deflator discussed above becomes a non-issue.

The disadvantage is that observations for two successive periods are required to construct one rate of change measure. Consequently sample size is reduced. Additionally, there can be no rate of change measure for the first period of production. (Because nothing was produced in the prior period there is no data for comparison.) Another problem is that first difference models appear to be much more sensitive to minor changes in the data.

Hence, they are perhaps less reliable for estimating parameters. (This will be commented on later.)

MEASUREMENT OF VARIABLES

Conceptually the dependent variable of interest is unit cost. As indicated previously, to pool observations from different programs it is necessary to deflate unit costs for each program to create comparable measures. Thus for testing purposes unit cost (UC) was measured as:

$$UC_{it} = \frac{AUC_{it}}{CAUC_i}$$

where

AUC_{it} = Average unit cost for lot t of program i.

$CAUC_i$ = Cumulative average unit cost for program i at the end of the program.

This measure deflates costs associated with individual lots produced with the overall average unit cost based on total costs and total quantities for the program. Hence UC is the ratio of a cost at a particular point in time to the program average cost. If average unit cost per lot were to decline consistently during a program's life, then UC for early lots would be above one and UC for later lots below one. If average unit cost per lot were to fluctuate above and below a trend, then UC would tend to fluctuate above and below one.

Note that the deflator, $CAUC_i$, can in principle change for a program as more lots are manufactured. Thus $CAUC_i$ (and consequently UC_i) depends on the specific given cost history for a

program. This creates a need to adjust quantity measures to the specific given quantity history for the program in order to make quantity measures comparable. Cumulative quantity (Q) at each lot produced was measured as:

$$Q_{it} = \frac{CUMQ_{it}}{TOTQ_i}$$

where

$CUMQ_{it}$ = Cumulative quantity at the algebraic lot midpoint of a particular production lot t for program i.

$TOTQ_i$ = Total program quantity = algebraic midpoint of final lot produced for program i.

Conceptually Q_{it} represents the proportion of the total program quantity that has been produced at each lot. Note that Q_{it} will increase from zero to one as t increases. If "learning" occurs then UC_{it} will decrease and Q_{it} will increase as t increases, reflecting the expected negative relationship.[6]

Perhaps the most commonly used measure of production rate in

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[6]Other approaches were also attempted to measure UC, first a learning curve was fit to the cost series for each program individually, then the learning curve was used to estimate the cumulative average cost at 1000 units. Then the average cost per lot was deflated by the cumulative average cost at 1000 units. This results in a UC measure which expresses lot average cost as a ratio to program cost at a fixed (1000) number of units, for all programs. To be consistent, Q was then measured as a ratio of quantity at lot t to 1000 units. Thus both costs and quantities were deflated by costs and quantities at 1000 units. This approach provided findings consistent with the findings reported in the paper. But there are two problems with the approach. First conceptually it is circular. (A learning curve is fit to arrive at a cost deflator which is used to create a cost measure which then becomes the dependent variable to which other learning curve models are then fit.) Second, most of the program specific learning curve models were insignificant, most likely because of few degrees of freedom.

past studies is production quantity. Boger and Liao (1990) review these studies and conclude that using production quantity to proxy for production rate leads to conceptually incorrect and statistically unreliable models. They recommend a ratio term be used to reflect production rate, where production quantity in any period is related to a standard production quantity, ideally the capacity production quantity or production quantity to which the manufacturer has tooled his facility. With this in mind production rate (PR) was measured as:

$$PR_{it} = \frac{PRODQ_{it}}{CAPQ_{it}}$$

where

$PRODQ_{it}$ = Production quantity in lot t for program i.

$CAPQ_{it}$ = Capacity quantity for program i.

The actual capacity quantity for each program was unknown. The maximum lot quantity observed during the life of a program was used as a surrogate. This surrogate is not unreasonable. Most programs tend to start off with a small number of units produced in early years and then build rapidly to a relatively constant number of units per year (with occasional cutbacks and a tapering off in the final years of a program). Maximum lot quantity reflects this "relatively constant number of units" and thus tends to reflect the standard capacity.[7]

Company-wide activity rate (CR) was measured as follows:

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[7]Tests were also conducted using the average lot size, rather than maximum lot size, as a deflator when measuring PR. Findings did not change.

$$CR_{it} = \frac{WIP_{it}}{AWIP_i}$$

where

WIP_{it} = Company-wide work-in-progress inventory during the year of lot t production.

$AWIP_i$ = Average yearly work-in-process inventory over the years of program i production.

Work-in-progress inventory is thus used as a surrogate for firm wide activity. As WIP increases, overhead costs should be spread over more (equivalent) units.

Industry activity rate was measured by industry capacity utilization. Capacity utilization measures were taken directly from Federal Reserve Board reports (as reproduced in Greer and Liao, 1983). Measures, provided on a monthly basis, were averaged to arrive at fiscal year capacity utilization. No deflation was required as the measures are expressed as percentages.

Fixed cost (FC) was measured as follows:

$$FC_{it} = \frac{PPE_{it}}{APPE_i}$$

where

PPE_{it} = Firm-wide property, plant and equipment during production of lot t.

$APPE_i$ = Average property, plant and equipment during the years of production on program i

This measure assumes that fixed costs are driven by capacity and that property plant and equipment provides a reasonable surrogate for firm-wide capacity.

In the first difference (cost change) models all variables

were constructed to reflect a ratio of values at two successive periods. In general:

$$\Delta \text{Variable}_{it} = \frac{\text{Variable}_{it}}{\text{Variable}_{it-1}}$$

Looking at company activity rate (CR), for example:

$$\Delta CR_{it} = \frac{CR_{it}}{CR_{it-1}} = \frac{WIP_{it}}{WIP_{it-1}}$$

In the first differences formulation, the various deflators used in calculating the original variables cancel out.

Each variable was transformed by taking the natural log of the dependent and various independent variables. Log-log regressions were fit to the transformed variables to estimate model parameters.

ANALYSIS

PROGRAM SPECIFIC MODELS

As a first step, individual learning curve models (equation 12) were estimated for each of the eight separate programs. This is the traditional approach and some findings of interest do result.[8] Table 3 contains estimated b parameters, model R^2 and learning curve "slopes." Slopes are calculated from b by slope = 2^b. Slopes are more intuitively meaningful: a slope of, say, .90 means that unit cost is reduced by 10% (i.e., 1.00 -.90) with a doubling of quantity. Negative (positive) b values translate to

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[8]Readers may note that the RIM-66E program is listed as having only two lots in Table 1. Fitting a learning curve to only two data points is not possible. In reality, two separate lots were produced in 1981 and one lot in 1982 making three data points available. The three points were used to fit the curve reported in Table 3. The two 1981 lots were combined into one annual lot and treated as one data point for all other analyses.

TABLE 3

LEARNING CURVE STATISTICS FOR INDIVIDUAL PROGRAMS

		Airframe Cost			Engine Cost			Flyaway Cost		
Program	Follow -On	b	Slope	R^2	b	Slope	R^2	b	Slope	R^2
RIM-24B	N	-.115	.92	.99***	-.585	.67	.28	-.093	.94	.59*
RIM-2D	N	-.034	.98	.14	-.153	.90	.63	-.077	.95	.67
RIM-2E	N	-.103	.93	.92***	-.160	.90	.19	-.111	.93	.61
RIM-66A	N	-.297	.81	.91**	.057	1.04	.20	-.309	.81	.88**
RIM-67A	N	-.229	.85	.79***	-.044	.97	.19	-.221	.86	.66**
RIM-66B	Y	.171	1.12	.56**	.017	1.01	.03	.166	1.12	.90***
RIM-67B	Y	.124	1.09	.02	.102	1.07	.61**	.062	1.04	.01
RIM-66E	Y	.123	1.09	.04	.097	1.07	.55	.171	1.13	.08

* prob. < .10

** prob. < .05

*** prob. < .01

slope values less (more) than one and represent decreasing (increasing) unit cost with increases in cumulative quantity.

Less than half of the individual models are significant--not surprising given the problem of few observations and low degrees of freedom--so results should be viewed with caution. But interesting patterns are evident. First, the variance of slope values is quite larger, generally falling between .80 and 1.10 across the three cost series and eight programs. This confirms the problem identified earlier: attempting to use a model fit to any one program to predict cost behavior expected for another program--even a program for the same type weapon system--is risky. The large variance also suggests that the b parameter for quantity may be picking up other influences on cost and exploration of other such influences may prove beneficial.

A second pattern is also of interest. With the exception of RIM-66A engine cost, the learning slopes for all costs of new design programs are less than one and the slopes for all costs of follow-on programs are above one. This provides some initial evidence in favor of hypothesis 6. New programs do apparently experience considerably greater cost improvement with increased quantity when compared to follow-on programs. The result also indicates the need to modify the empirical model when analyzing the pooled observations.

POOLED RESULTS

If new designs can be expected to experience systematically different learning rates than follow-on series, estimating one

learning parameter for pooled observations will be misleading. The models presented so far included a single quantity term (Q^b). To allow for different rates between new and follow-on programs, the single term can be replaced with two:

$$UC_Q = a\ Q^{Nb}\ Q^{Fc}$$

where

N = 1 if a new program, 0 otherwise.

F = 1 if a follow-on program, 0 otherwise.

b = Learning parameter for new designs.

c = Learning parameter for follow-on series of existing designs.

Separate parameters can then be estimated for new and follow-on programs.

Results from fitting both single and duel parameter models to the pooled observations, in both "cost level" and "cost change" (first difference) form, are in Table 4. Note that two related patterns are evident. First, looking at the duel parameter models, across the three different cost series and the two model approaches:

$$slope_{new} < slope_{follow\text{-}on}$$

Thus the general tendency for new programs to experience greater learning is evident here in the pooled analysis.

Second, comparing single versus duel parameter models, note that $slope_{new} < slope_{all} < slope_{follow\text{-}on}$. This merely confirms intuition that failing to distinguish new from follow-on programs and estimating a single parameter for Q provides a slope value that is an "average" of new and follow-on programs. Such an approach

TABLE 4

LEARNING CURVES - NEW VERSUS FOLLOW-ON PROGRAMS

	SINGLE PARAMETER MODELS			DUEL PARAMETER MODELS				
VARIABLE	Q			Q_{New}		$Q_{Follow-On}$		
PARAMETER[1]	b	Slope	R^2	b	Slope	c	Slope	R^2
Cost Level								
Flyaway	-.132 (-2.76)***	.91	.14	-.150 (-2.96)***	.90	-.068 (-.88)	.95	.17
Airframe	-.167 (-3.27)***	.89	.19	-.193 (-3.60)***	.87	-.074 (-.90)	.95	.23
Engine	-.084 (-1.45)	.94	.04	-.090 (-1.43)	.93	-.066 (-.69)	.96	.05
Cost Change								
Flyaway	-.093 (-.73)	.93	.01	-.161 (-1.38)	.89	.484 (2.17)*	1.40	.21
Airframe	-.256 (-1.79)*	.83	.08	-.319 (-2.33)**	.80	.284 (1.08)	1.22	.21
Engine	.094 (.61)	1.07	.01	.070 (.44)	1.05	.305 (.99)	1.23	.03

* prob. < 10
** prob. < .05
*** prob. < .01
1: t-value in parentheses.

discards relevant explanatory information.

FULL MODEL RESULTS

Table 5 presents results from estimating models with all relevant variable included. Since these multivariate models control for the impact on UC of each of the potential cost drivers, these models are the most appropriate to use for testing the hypotheses.[9]

Cumulative Quantity (Q): Hypothesis 6 predicted greater learning for new programs when compared to follow-on programs. Consistent with the previous (Table 4) results, for all models in Table 5 learning coefficients for new programs (b) are less than learning coefficients for follow-on programs (c). Formal F tests were conducted to determine if this pattern was statistically significant. For both airframe cost and flyaway cost, b values were significantly less than c values (probability < .05) and thus support for hypothesis 6 was found. The results for engine cost were insignificant.

Hypothesis 1 predicted that learning parameters would be negative, i.e., that cost reduction would occur with increases in cumulative quantity produced. The significant negative b values, in the cost level models, for all three cost series, indicates that significant learning does occur for new designs. The corresponding insignificant negative c values suggests no apparent learning for

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[9]Since the hypotheses are directional one-tailed tests of significance are used.

follow-on programs.

It must be acknowledged that there are substantial differences in the b and c parameters between the cost level and cost change models. To explore this issue some simulations were run, estimating model parameters using constructed data.

First a series of cost and quantity data with a known "perfect" or "true" learning rate was created. As expected estimating both cost level and cost change models produced models with $R^2 = 1$ and parameters exactly equal to the known true slope. This confirms that in principle both approaches are equivalent. Then two additional cost/quantity series were constructed, each by adding a small amount of random noise to the "true" series, and models were re-estimated. For the cost level models, R^2 dropped only marginally below 1 and parameter estimates were trivially different from the known "true" parameter. For the cost change model, R^2 dropped significantly and parameter values diverged substantially from the "true" parameter. The basic conclusion to be drawn from these simulations is that models estimated using the cost change approach are considerably more sensitive to changes in the data and, therefore, perhaps less reliable for estimating true parameters.

<u>Production Rate</u> (PR): Findings for production rate are somewhat inconsistent. Significant negative d parameters for flyaway cost (in both cost level and cost change models) reflect a general tendency for total unit cost to decline as production rate increases. This appears to be caused by the reduction in

TABLE 5

MULTIVARIATE MODELS

VARIABLES:	Intercept	Q_{New}	$Q_{Follow-On}$	PR	CR	IR	FC	
PARAMETERS[1]:	a	b	c	d	f	g	h	R^2
Cost Level								
Flyaway	2.32	-.144 (-2.70)***	-.010 (-.14)	-.197 (-2.60)***	-.907 (-2.07)**	-.880 (-1.39)*	1.34 (1.46)*	.52
Airframe	.025	-.191 (-3.40)***	-.036 (-.47)	-.197 (-2.47)***	-.909 (-1.97)**	-.412 (-.62)	1.56 (1.61)*	.56
Engine	8.28	-.145 (-1.81)**	-.077 (-.70)	.167 (1.47)*	-.681 (-1.03)	-2.03 (-2.12)**	.45 (.32)	.19
Cost Change								
Flyaway	-2.90	.049 (.41)	.593 (2.90)***	-.301 (-3.20)***	-.922 (-1.33)*	-.836 (-.77)	2.70 (2.07)**	.48
Airframe	-3.32	-.302 (-1.84)**	.386 (1.39)*	-.040 (-.31)	-1.27 (-1.34)*	-.082 (-.06)	3.34 (1.88)**	.31
Engine	-1.41	.140 (.71)	.189 (.57)	-.017 (-.11)	-.950 (-.84)	-2.90 (-1.65)*	1.23 (.59)	.10

* prob. < .10, one-tailed test
** prob. < .05, one-tailed test
*** prob. < .01, one-tailed test

1. t-value in parentheses.

airframe cost with increased production rate (significant negative d in the cost level model). The reduction in airframe cost was apparently sufficient to offset an increase in engine cost (significant positive d in the cost level model). These findings are also consistent with hypothesis 10 that the influence of production rate on prime contractor and subcontractor cost may be different. Such a conclusion, however, must be tentative given the lack of significance of d for both airframe and engine cost in the cost change models.

Company Activity Rate (CR). Results for the company-wide activity rate (of the prime contractor) are consistent with hypotheses. Several patterns are worth noting. First, values for parameter f are negative in all models, consistent with increased activity reducing per unit cost. Second, comparing estimated parameters for airframes and engines, $f_{airframe}$ is less than f_{engine}. And $f_{airframe}$ is significantly negative while f_{engine} is insignificantly different from zero. This supports hypothesis 7.2. The prime contractor's activity rate does drive costs of components actually manufactured by the prime contractor, but the cost of subcontracted components is unaffected. Additionally note that $f_{flyaway}$ is also significantly negative. The fact that "internal" airframe cost comprises a far larger proportion of flyaway cost than does "external" engine cost would explain the effect of activity rate on total flyaway cost.

Fixed Capacity Cost (FC): Results for FC are also consistent with hypotheses. Values for parameter h are uniformly positive,

consistent with higher prime contractor fixed costs driving up unit production cost. But while h values are significant for airframe cost they are not significant for engine cost. Thus prime contractor capacity costs are relevant to explaining internally manufactured components and do not affect subcontracted items. Fixed cost does explain flyaway cost ($h_{flyaway}$ is significantly positive). Again the likely explanation is that airframe cost comprises a large proportion of flyaway cost.

Industry Activity Rate (IR): Results for IR are consistent with hypotheses. Values for parameter g are uniformly negative, consistent with greater industry activity reducing per unit cost. But again different results are evident for prime and subcontracted costs. Values for g are significant for engine cost. Apparently industry capacity utilization does reflect information concerning the degree to which subcontractors may be able to spread fixed costs and reduce per unit cost. In contrast values for g are insignificant for airframe cost. This is consistent with the idea that by including prime contractor PR, CR and FC in the model, IR may be redundant, and hence unimportant. Note that IR is significant in explaining flyaway cost (significant g in the cost level model). Given that flyaway cost is the aggregate of both prime and subcontracted costs, finding some ability of industry capacity utilization to explain flyaway cost is not surprising. The pattern of parameters reinforces these findings:

$$g_{engine} < g_{flyaway} < g_{airframe}.$$

Finding a parameter value for flyaway cost that is an "average" of

the separate parameters for the engine and airframe costs is consistent with flyaway cost being an aggregate of the two.

EXTENSIONS

MODEL PREDICTION ERRORS

Due to the limited number of missile systems no holdout sample is available for model validation. The only data available for testing model performance is the same data used to derive the models. While not ideal, observing the performance of alternative models, created by selectively including variables, does provide some indication of the ability of variables to enhance prediction.

Current cost estimation practices rely most heavily on the traditional learning curve model (perhaps enhanced with the inclusion of a production rate term). As a benchmark, learning models were first estimated including only cumulative quantity (Q) as an independent variable (i.e., equation 17). Then separate models were estimated adding one additional variable (PR, CR, IR, or FC) to the learning model. Finally a model including the variables found significant during hypothesis testing (Table 5, cost level models) was estimated for each cost series.

The criteria used to measure model performance was the absolute prediction error, measured by the difference between predicted unit cost and actual unit cost as a percentage of predicted cost. Table 6 provides results. The "improvement" column in the table reflects the proportionate reduction in error achieved by adding variables to the benchmark Q model. The "ranking" column provides a rank ordering of the models (1 = best)

based on minimum error (and maximum improvement).

Not surprisingly the models including all significant (sig.) independent variables are most accurate. For all three cost series average absolute prediction error is about 20%. For both airframe and flyaway cost, using all significant variables in the models reduces error, relative to the benchmark learning model, by about 33%. The relative improvement for engine cost is considerably less dramatic.

The results also suggest which variables have the most important impact on reducing prediction error. For both flyaway and airframe cost, including either PR or CR to the benchmark model reduces prediction error most substantially. For engine cost, IR provides the most noticeable marginal improvement. The general conclusion to be drawn is that the inclusion of rate terms reduces error. But the value of specific rate terms depends on the cost series. Prediction of internal cost (i.e., airframe manufactured by the prime contractor) is improved most by attention to firm specific rate measures - PR and CR. Prediction of external costs (i.e., subcontracted engine cost) is improved most by attention to a broader industry rate measure - IR. The pattern is consistent with the conclusions suggested by the hypothesis tests.

EXPLAINING PREDICTION ERRORS

Defense procurement, particularly for major weapon systems, is specialized in nature. Both the product and market are not typical of products and markets in general. The market for defense systems is unusual, with a single (monopsonistic) buyer and usually

TABLE 6

MODEL PREDICTION ERRORS

Flyaway Cost	Model[1]	Average Absolute Error[2]	Improvement Percentage[3]	Ranking
	Q	28.8%	-	6
	Q,PR	20.7%	28.1%	2
	Q,CR	23.7%	17.6%	3
	Q,IR	28.3%	1.7%	5
	Q,FC	28.0%	2.7%	4
	Sig.	19.1%	33.1%	1
Airframe Cost				
	Q	30.5%	-	6
	Q,PR	22.8%	25.3%	2
	Q,CR	24.7%	18.8%	3
	Q,IR	29.1%	4.6%	4
	Q,FC	29.7%	2.6%	5
	Sig.	20.4%	33.8%	1
Engine Cost				
	Q	23.3%	-	6
	Q,PR	23.1%	.5%	5
	Q,CR	22.4%	3.7%	3
	Q,IR	22.3%	4.0%	2
	Q,FC	22.8%	1.9%	4
	Sig.	21.7%	6.7%	1

1. Model includes the variables listed. Sig. means inclusion of only the variables that were significant in the Table 5 cost level models.

2. Absolute error = $|(\text{predicted} - \text{actual})/\text{predicted}|$

3. Improvement percentage = (Average absolute from benchmark model - Average Absolute error from alternative model) ÷ Average absolute error from benchmark model. A model including only Q is the benchmark model.

only a few (oligopolistic) sellers. Prices are determined primarily through a bid and negotiation process. A bid is accepted and a contract for a specified number of units is negotiated prior to production. Prices (costs to the government) are specified in the contract and are based on costs incurred ("cost plus") using some agreed upon formula. Cost estimates and their source are disclosed at the time of contract negotiation, so some agreement on the validity of cost estimates is established up front.

The analysis so far has focused on what can be labeled "production" cost drivers; the factors analyzed (quantity, various activity rates, fixed cost) all relate to what it costs a manufacturer to produce an item. An implicit assumption adopted so far is that buyer cost is directly related to the cost incurred by the manufacturer during production. The assumption is reasonable given some form of cost-based pricing arrangement. The fact that the set of production cost drivers were useful in explaining buyer cost additionally supports the assumption.

Assume that there is a buyer cost that can be "justified" by manufacturer cost. This buyer cost would depend on, and be explainable by, the production cost drivers. Under cost-based acquisition, notions of this justified buyer cost (UC_j) would serve as a starting point for negotiation of an actual buyer cost (UC_a). But actual buyer cost would likely be influenced by factors other than the production cost drivers. Hence there would be some deviation (DEV) between actual buyer cost and justified buyer cost:

$$UC_a = UC_j + DEV$$

One question remaining is what factors may cause buyer cost to differ from justified cost? When might DEV be relatively high or low? The degree to which UC_a will differ from UC_j should depend on the relative strengths of the negotiating positions of the buyer and manufacturer, and conditions influencing the negotiations. Several variables are discussed below.[10] Each is an attempt to reflect some broad feature of the environment at the time negotiation and procurement occur. For each factor, how that factor might influence prices offered by a contractor and accepted by DoD are discussed. Hence each factor is a potential explainer of DEV. To the extent that these factors influence negotiations they provide possible explanations for differences between UC_a and UC_j.

Defense Spending. What was the political and budgetary environment like at the time of production? Were constraints being imposed on defense spending? Were defense or non-defense programs favored? It was felt that contractors would have less incentive to offer a low price (and perhaps government negotiators would have less pressure on them to demand a low price) if the political environment appeared favorable to defense spending. The degree of defense spending was measured by defense spending as a percentage

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[10]Obviously the variables examined here don't exhaust the possible factors that may influence cost. Contract type, the presence of competition or a second source, various contract incentives are relevant. The variables selected here were limited by two considerations. First, data availability. Second, and more to the point, since the analysis is attempting to explain year-to-year differences in cost within a set of programs, the desire was to examine factors that also vary from year-to-year.

of total federal spending at time t, the year of production. A positive relationship between defense spending and cost was expected.

General Economic Conditions: Economic conditions - growth or contraction - may influence program cost. If the economy is robust, demand for products should be relatively greater, markets for alternative products supplied by contractors may be more plentiful, and incentives to "give" on price for a particular defense contract may be reduced. When economic contraction occurs, defense programs may appear more appealing and the increased incentives to seek such contracts may result in lower prices. Economic conditions were measured by the rate of growth in GNP from time t-1 to t. A positive relationship between GNP growth and cost was expected.

Commercial Business: Government contractors also have business segments devoted to commercial products. Evidence (Greer and Liao, 1986) indicates that defense business is less profitable and more risky than commercial business and that defense business may be more attractive (to absorb a firm's overhead burden) when commercial opportunities are less available. This suggests that the incentive for a contractor to "give" on price may be related to the amount of commercial business available. Amount of commercial business was measured as the proportion of commercial business activity to total business activity at time t. A positive

relationship between commercial business and cost was expected.[11]

Inflation: Inflation makes future dollars worth less than current dollars. When the inflation rate is high contractors may compensate for its effect by building a cushion into the price they offer in order to cover expected higher costs. Lehman (1988) argues that acquisition process itself is structured so as to encourage raising future prices due to past inflation. This occurs because the Program, Planning and Budget System builds past inflation into future cost estimates. Contractors, aware of this upward bias caused by the built-in inflation factor, automatically raise prices to the level they know is permitted by the inflation factor. Tyson et. al., (1989) also discuss this issue, arguing that costs will be too high or too low depending on whether future inflation is less than or greater than anticipated inflation. To the extent that past inflation leads to an increment being added to negotiated costs, costs may be explainable with reference to past inflation. Inflation was measured by the rate of change in the producer price index from t-2 to t-1. A positive relationship between inflation and cost was expected.

Time: The environment in which military acquisitions occur has not remained static. Scrutiny of the acquisition process by the Congress and the public has increased. Calls for increased competition are heard. Oversight, regulations and procedures governing acquisition have been revised and altered over the years.

[11] Data to measure proportion of commercial business was unavailable for 12 observations; hence tests are based on only 35 observations.

Tyson et. al. (1989) describes four major eras in defense acquisition, each characterized by different acquisition initiatives and processes. One additional question is whether these changes have lead to any consistent trend on cost over time. A year variable (fiscal year at time of production) was included in the analysis to examine any time trend.

Dependent Variable: A measure of the degree to which actual cost (UC_a) differed from justified cost (UC_j) was needed. For each of the three cost series, UC was regressed on the specific production cost driver variables that had been found to be significant in the previous analysis (i.e., Table 5, cost level regressions). These regression were used to predict unit cost. These predicted unit costs were interpreted at the cost that is explainable by the production cost drivers and consequently "justified". Empirically, the difference between actual and predicted cost was measured as a percentage:

$$DEV = \frac{\text{Actual UC} - \text{Predicted UC}}{\text{Predicted UC}}$$

Thus the variable DEV is measured as the degree to which actual cost exceeds or is less than the cost predicted by knowledge of the production cost drivers. This measure is the same that was used in the Table 6 analysis of prediction errors, except absolute value operators are absent. An attempt to explain this measure is equivalent to an attempt to explain the variance in unit cost that is left unexplained by the production cost drivers.

Tests: Table 7 provides simple pairwise correlations between

DEV and the hypothesized explanatory variables.[12] There are significant results for four of the five variables. The correlation signs suggest the following patterns: There is a trend toward higher cost over time (positive correlation with fiscal year). Cost tends to decrease as defense spending increases (contrary to expectations). Cost tends to increase with GNP growth. This is consistent with a robust economy resulting in a stronger negotiation position for a contractor and a resultant higher cost to DoD. Cost tends to increase with higher rates of inflation. This is consistent with an inflation "premium" being built into negotiate cost. Results for commercial business are non-significant.

These patterns must be interpreted with caution. Table 8 shows pairwise correlations between all of the explanatory variables that are significant and, in several cases, very high. For example, fiscal year, defense spending and GNP growth are all inter-correlated at .90 or greater. The correlation matrix indicates that during the years encompassed by the observations, defense spending (as a proportion of federal spending) decreased, GNP growth rate increased, commercial business percentage increased and inflation rate increased.

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[12]This approach is similar to correlating residuals from the production cost driver regressions with the hypothesized explanatory variables. The difference is that the production cost driver regressions were of log-log form and hence the residuals are not expressed as cost errors but rather as log cost errors. The prediction errors analyzed here are actual cost minus predicted cost, not actual log cost minus predicted log cost. Results from both approaches were similar.

TABLE 7

CORRELATION OF PREDICTION ERRORS
WITH EXPLANATORY FACTORS

Variables	Flyaway Cost	Airframe Cost	Engine Cost
Defense Spending	-.22*	-.33**	-.21*
GNP Growth	.20*	.33**	.23*
Commercial Business	.08	.15	-.04
Inflation	.25**	.34***	.30**
Fiscal Year	.19	.29**	.22*

* prob. < .10
** prob. < .05
*** prob. < .01

TABLE 8

CORRELATIONS BETWEEN EXPLANATORY FACTORS

Variables	1	2	3	4	5
1. Defense Spending	1.00				
2. GNP Growth	-.91	1.00			
3. Commercial Business	-.79	.62	1.00		
4. Inflation	-.81	.75	.58	1.00	
5. Fiscal Year	-.96	.94	.65	.79	1.00

Given the high intercorrelations, it is difficult to identify which individual factor or factors may have influential cost. On the basis of the Table 7 correlations, inflation is the strongest explainer. For each of the three cost series, the correlation for inflation is the highest and most significant of the five factors. As a further test, stepwise regressions were run, allowing the stepwise procedure to select the most important variable. For all three cost series, inflation was selected first. No additional variable was a significant explainer of cost, given inflation.

Perhaps the relatively stronger results for inflation is plausible. The links between inflation rate and actual buyer cost are relatively direct. As discussed before, the links rest on explicit procedures in the planning and budgeting process that factor past inflation into cost estimates that form the basis for negotiating actual buyer cost (Lehman, 1988; Tyson et. al., 1989). The links between general environmental conditions such as defense spending and GNP with the cost of a particular individual system are more tenuous. If inflation is the driving factor, the results for the other variables are likely due to their high correlation with inflation.

SUMMARY AND CONCLUSIONS

The purpose of this paper was to identify and investigate factors (cost drivers) that influence and therefore explain unit cost of systems. The premise was that average unit costs per production lot would vary as a function of conditions surrounding

the manufacture of each lot. The analysis started by presenting some simple functional models of unit cost; the objective of these models was to identify potential cost drivers and isolate the expected effect of these cost drivers on unit cost. Empirical models were then developed to test the expected relationships. Tests were conducted using data from eight surface-based tactical missile systems manufactured by General Dynamics. Distinctions were made between two kinds of programs (new designs versus follow-on series) and between the cost of two types of system components (internally prime contractor manufactured components versus externally subcontracted components). The role of particular factors in explaining cost was expected to differ according to these distinctions. The broad findings were as follows:

1. Significant learning (cost reduction) is evident with increases in cumulative quantity produced during the manufacture of new designs. Learning during the manufacture of new series of existing designs is not evident.

2. The role of production rate as a cost driver is ambiguous. The results indicated a negative relationship between unit cost production rate for prime contractor manufactured components but a positive relationship for subcontracted components. No general statement concerning production rate as a cost driver is possible. The impact of production rate on cost may be situation specific. This conclusion is consistent with the previous findings reported in the literature (e.g., Smith, 1980).

3. Company-wide activity is a potentially important cost

driver. Unit cost decreases with increases in company-wide activity. This is consistent with the idea that greater activity permits the assignment of fixed cost to a wider corporate output and consequently the assignment of less fixed cost burden to a particular program. This result holds for the cost of components manufactured by prime contractors. The result does not hold for the cost components subcontracted.

4. Although aggregate total system unit cost (flyaway cost) was found to be reduced with increases in prime contractor activity, the relevance of prime contractor activity rate to explaining total system cost is likely to depend on the relative proportion of total system cost composed of internally manufactured components and externally subcontracted components.

5. Company-specific fixed capacity cost is a potentially important cost driver. Unit costs increase with increases in property, plant and equipment. Again this result held for prime contractor manufactured components, not for subcontracted components.

6. The relevance of fixed capacity costs to explaining aggregated total system unit cost (flyaway cost) is also likely to depend on the relative proportions of prime contractor and subcontracted components in the total system.

7. Industry activity rate is relevant to explaining the cost of externally subcontracted components. Unit cost decreases as capacity utilization increases. This suggests that industry capacity utilization may provide a workable surrogate for business

activity of subcontractors. It also confirms, using a different approach and different sample, the findings of prior research (Greer and Liao, 1986).

8. The relevance of capacity utilization in explaining total cost of a system is likely to depend on the relative proportion of subcontracted components in total cost.

9. Cost prediction error can be reduced materially by enhancing a learning curve model with inclusion of additional production cost driver variables. Variables reflecting relevant activity rates appear to add the most to prediction accuracy.

10. Costs to the buyer are influenced by factors beyond those that influence production cost. Of these factors, inflation rate appears to be most important. The degree to which cost to DoD exceed cost that can be "justified" in terms of production factors is associated with the past rate of inflation. This is consistent with an inflation premium being built into cost.

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